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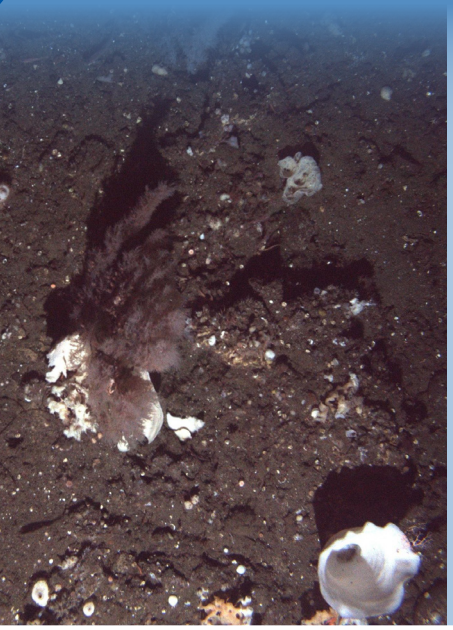
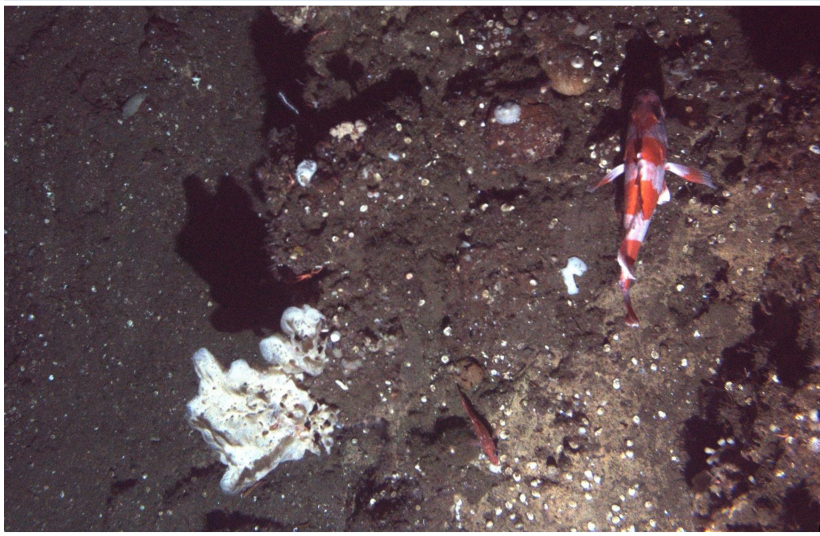


Autonomous Underwater Vehicle (AUV) Survey at The Footprint and Piggy Bank in the Southern California Bight, 2011



December 2020

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
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Cover images: (top left) AUV image of corals and sponges in the study area, October 2011. (bottom left) The AUV being brought back on deck after a dive. (top right) A flag rockfish on rocky substrate, photographed by the AUV. (bottom right) The AUV at the surface. Photographs by the AUV Survey Team, NMFS/NWFSC.

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NOAA FISHERIES

Autonomous Underwater Vehicle (AUV) Survey at The Footprint and Piggy Bank in the Southern California Bight, 2011

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Abstract

Monitoring fish populations at rocky offshore banks is challenging, but vital for the sustainable management of groundfish stocks. Deep banks provide important rocky habitats for commercially important species and can also act as a refuge from fishing. Imagery acquired by manned and unmanned underwater vehicles can be used to supplement data from more traditional trawl surveys, which are not suited to high-relief substrates. To explore the potential of three different vehicles to quantify groundfish, surveys were conducted with a submersible (SUB), a remotely operated vehicle (ROV), and an autonomous underwater vehicle (AUV) at two banks in the Southern California Bight. Here we present the results of the AUV survey, carried out in October 2011 based on a stratified random sample design. In total, 64,470 m^2 were surveyed across The Footprint and Piggy Bank, and 22,249 fishes in 54 taxa were recorded from the AUV imagery. The total number of fish estimated for the area surveyed at the two banks was 5,511,922. We observed a diverse rockfish assemblage numerically dominated by three dwarf rockfish species: halfbanded rockfish *(Sebastes semicinctus*), shortbelly rockfish (*S. jordani*), and squarespot rockfish (*S. hopkinsi*). There were also a number of commercially important species, including cowcod (*S. levis*), bocaccio *(S. paucispinis*), lingcod (*Ophiodon elongatus*), Pacific hake *(Merluccius productus*), and sablefish (*Anoplopoma fimbria*). The downward-facing cameras on the AUV enabled the identification of a large number of flatfish, including petrale sole (*Eopsetta jordani*), rex sole (*Glyptocephalus zachirus*), and slender sole (*Lyopsetta exilis*). We observed species distribution patterns associated with changes in depth and substrate type at both banks. The Footprint had higher abundances of dwarf rockfish species and lingcod, whereas Piggy Bank had more bank rockfish and thornyheads, likely due to its deeper depth. Total estimated biomass of a subset of commercially important species was 246,559 kg. Finally, we compared fish lengths obtained from the AUV stereo imagery to data from the U.S. West Coast trawl survey collected in the Southern California Bight in the same year. For most species, mean size was similar between both methods, but differences were evident for a few species.

Acknowledgments

We thank the officers and crew of the RV *Shearwater* and the Channel Islands Marine National Sanctuary for their assistance. This work was supported by the National Marine Fisheries Service Office of Science and Technology.

1 Introduction

To ensure long-term sustainability of marine fish populations and the economic benefits of associated fisheries, the Magnuson–Stevens Fishery Conservation and Management Act requires periodic assessment of fish stocks and their habitats. Assessments generally rely on long-term surveys of stock abundance and age composition to estimate current stock status and forecast future trajectories under management alternatives. For west coast groundfish, historically this information has been provided by bottom trawl surveys (Keller et al. 2017).

Despite the value of trawl surveys for monitoring many groundfish stocks, they are of limited applicability in rocky areas due to the rugged nature of the terrain. In addition, protected areas, even if accessible to trawling, should be monitored with low-impact methods to maintain their protected status. Methodologies are needed that can provide cost-effective surveys in rocky and protected areas to provide information for accurate population assessments. To test the potential of various survey tools for monitoring groundfish, a field study was carried out using a human-occupied submersible (SUB), a remotely operated vehicle (ROV), and an autonomous underwater vehicle (AUV) at two banks in the Southern California Bight. This report focuses on the results of the AUV surveys, which were carried out at The Footprint and Piggy Bank down to 500 m from 10–17 October 2011.

Our primary aim was to design and implement a survey of groundfish and their habitat within the study area to determine the utility of a bottom-tracking AUV as a tool for conducting low-impact monitoring in untrawlable or protected areas. The specific objectives of our project using visual survey techniques from a SeaBED-class AUV were to: 1) collect data on counts and sizes for groundfish and other associated fishes; 2) estimate densities and associated precision; 3) estimate size compositions; 4) estimate abundance and biomass and associated precision; and 5) estimate biodiversity of fish species within the study site.

2 Methods

2.1 Study Site

The survey was conducted in the Southern California Bight offshore of Santa Cruz Island. The Footprint is about 10 km^2 in area, ranging in depth from 80 to 500 m, and Piggy Bank is about 30 km^2, ranging in depth from 275 to 900 m. The study area encompassed large portions of Footprint and Piggy Banks and surrounding waters to a depth of 500 m (Figure 1).

2.2 Survey Design

A stratified random grid-based sampling design was used, similar to one used by the U.S. West Coast trawl survey since 2003. The entire study site was divided into continuous grid cells of 250 m × 250 m (Figure 1). Grid cells that did not completely reside in the sampling area were excluded from selection. The pool of grid cells was divided into three strata, based

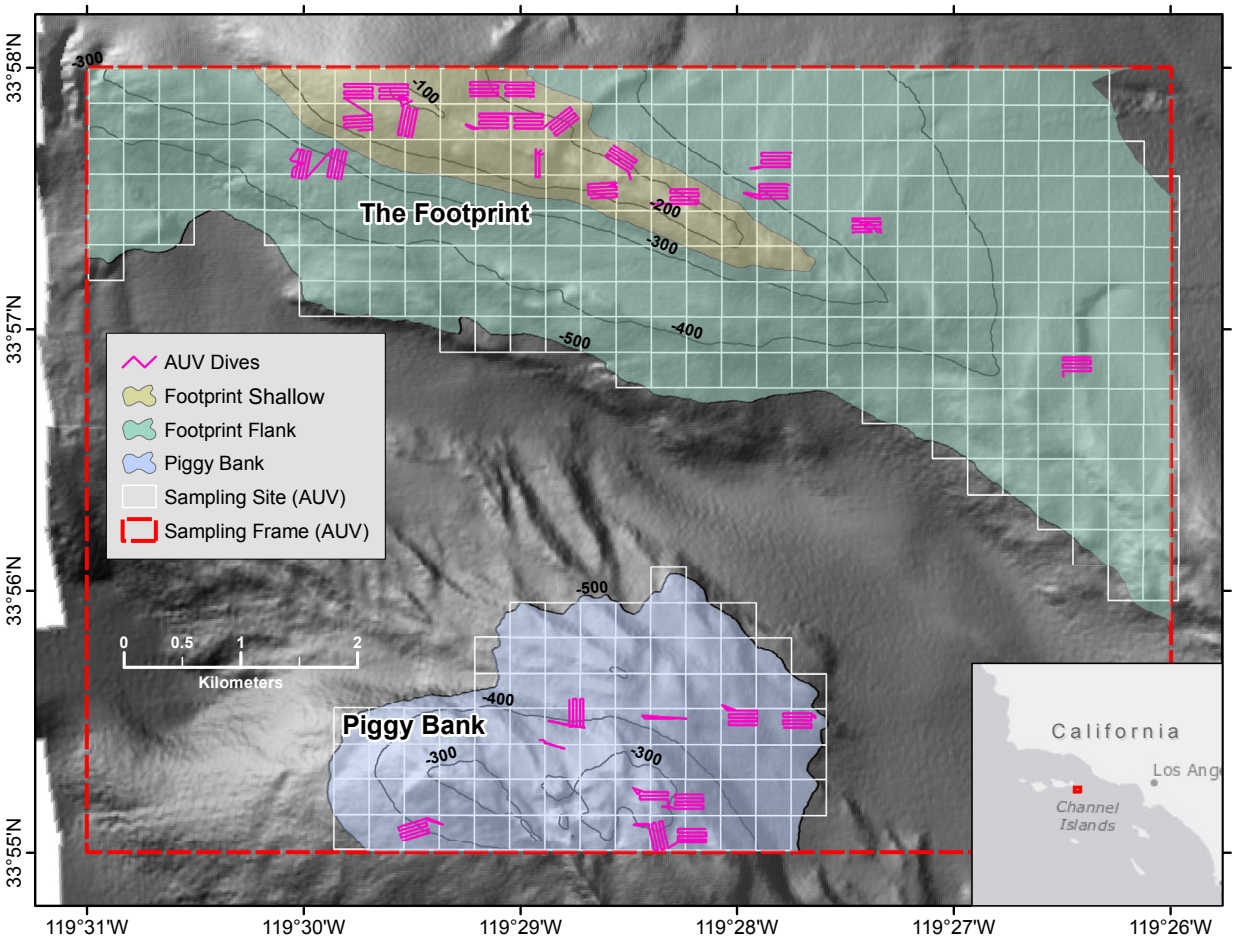

Figure 1. Locations of the 27 sampling sites in the study area.

Table 1. Sampling effort by study site.

Site	Site area (m^2)	Number of cells	Area surveyed (m^2)[a]
Footprint Shallow	4,051,623	13	25,938
Footprint Flank	11,642,729	6	17,850
Piggy Bank	5,110,815	8	22,682

[a] Total area of the AUV images analyzed.

on general location and depth: the top of The Footprint to the 200-m contour (referred to as "Footprint Shallow"), the slope of The Footprint from 200 to 500 m (referred to as "Footprint Flank"), and Piggy Bank from the surface to the 500-m contour. The area of each stratum is reported in Table 1. Cells to be surveyed were selected randomly in each stratum. Grid cells that straddled two strata were placed in the stratum in which the cell encompassed more than 50% of the cell area. Within each cell, the AUV was programmed to survey a transect pattern covering the majority of the cell at a fixed height (3–4 m) above the seafloor. Transects consisted of five 200-m lines connected by four 25-m lines, for a total track distance in each cell of 1.1 km. Adjacent or nearby cells enabled multiple cells to be sampled during one dive.

2.3 Image Collection

Surveys were carried out from 10–17 October 2011 from the National Marine Sanctuary research vessel, the RV *Shearwater*. Images of the study area were collected using a SeaBED-class, bottom-tracking AUV.[1] The SeaBED AUV uses an inertial navigation system to continuously calculate relative position, heading, and velocity of the vehicle over the seafloor (Powell et al. 2018). To image the seafloor, the AUV was equipped with high dynamic range, digital, color, 5 MP photographic cameras arranged in a stereo pair directed downward and orthogonal to the seafloor, and a third high dynamic range, digital, color, 11 MP photographic camera directed forward at approximately 35°. The AUV was programmed before each dive to follow a specified, evenly spaced transect path. It was programmed to take photographs once every 10 seconds from a consistent altitude—either 3 m or 4 m—above the seafloor, at a forward speed of 0.25 m/s (~0.5 knot [kn]). Images were downloaded after each dive and color corrected prior to analysis.

All nonoverlapping color-corrected digital stills from the long transect legs of each survey pattern were selected for review. The downward-looking port camera images were reviewed following the cruise and fishes were identified and counted. Fish lengths were measured using the stereo imagery from the paired downward-looking cameras. Photographs from the angled camera were used to assist in species identification only. As the altitude maintained by the AUV changed, so did the image area. The area of each image was estimated using the measured altitude above the seafloor and the calibrated camera field-of-view angles. Seafloor habitats in each photograph were categorized using a two-character code based on substrate type (Greene et al. 1999). The first character signified the primary habitat type that covered greater than 50% of the field of view, while the second character defined the secondary habitat type (covering between 20% and 50%). If the primary habitat coverage exceeded 80%, that letter was denoted twice (e.g., CC for cobble–cobble).

[1] Seabed Technologies, Inc., Falmouth, Massachusetts: http://www.seabedtech.com/.

2.4 Enumeration of Fish

All fishes were identified to the lowest possible taxonomic level and counted in all nonoverlapping images to avoid double counting of individuals. Fish that could not be identified to species were identified to family, genus (e.g., unidentified rockfish, *Sebastes* spp., or unidentified thornyhead, *Sebastolobus* spp.), or subgenus (e.g., white-spotted red rockfish group, *Sebastomus* spp., which includes rosethorn [*Sebastes helvomaculatus*], starry [*S. constellatus*], pink [*S. eos*], greenspotted [*S. chlorostictus*], greenblotched [*S. rosenblatti*], rosy [*S. rosaceus*], freckled [*S. lentiginosus*], honeycomb [*S. umbrosus*], whitespeckled [*S. moseri*], southern [*S. notius*], pink-rose [*S. simulator*] and swordspine [*S. ensifer*] rockfish.)

2.5 Length Estimates

The total length (cm) of each fish was estimated from stereo imagery to the nearest 1 cm. Not all fish could be measured directly from the stereo images, in most cases because part of the fish was obstructed from view or was not visible in both images of the stereo pair. For those fish, we estimated the length visually to the nearest 5 cm using nearby measured features for reference. Size distributions and mean length for each species were compared to the results of the U.S. West Coast Groundfish Bottom Trawl Survey. Trawl data were downloaded from the NOAA Fishery Resource Analysis and Monitoring Division's Data Warehouse,[2] and a subset was used in the analysis which included data from 2011 collected at depths <500 m and latitude <34.5°. Comparisons were limited to species where over 50 individuals were measured in both the AUV and the trawl survey. Histograms were used to compare size distributions obtained with the different methods, and mean lengths were compared using nonparametric Kruskal–Wallis tests.

2.6 Estimating Abundance and Biomass

For each of the three strata (Footprint Shallow, Footprint Flank, and Piggy Bank), we estimated total abundance and biomass of each species and selected higher-level taxonomic groups. To estimate abundance, first we calculated fish density per cell. The total number of fish observed in the AUV images for each cell was summed and then divided by the area surveyed in that cell. Then we calculated mean densities, coefficients of variation (CV), and 90% confidence intervals for each of the focal areas using a bootstrap of 1,000 samples (resampling the cell densities within that area with replacement). Mean fish densities were expanded to total abundance and variance for each focal area by multiplying mean cell densities by the total areas of Footprint Shallow, Footprint Flank, and Piggy Bank. The coefficient of variation was calculated as:

$$CV = \frac{\sigma}{\mu}$$

where μ is the mean of the cell densities and σ is the standard deviation of the cell means.

[2] https://www.webapps.nwfsc.noaa.gov/data/map

Biomass of each individual was estimated from known length–weight relationships (see Appendix A) as:

$$B = a \times TL^b$$

where TL = total length estimated from the stereo imagery. Species coefficients for a and b are listed in Appendix A. Biomass estimates were then summed for each grid cell and divided by the cell area to obtain biomass density. Then we calculated mean biomass, coefficients of variation (CV), and 90% confidence intervals for each of the focal areas using a bootstrap of 1,000 samples (resampling the biomass densities within that area with replacement). One grid cell was excluded from the biomass estimate for Piggy Bank, as one of the paired cameras did not function, so we were unable to obtain length estimates for that dive. Poachers, sculpins, eelpouts, combfish, and hagfish were not included in the biomass estimates, as they are not commercially harvested and, to our knowledge, length–weight relationships have not been published for these groups.

2.7 Characterization of Fish Diversity at the Study Sites

Sample-based rarefaction curves were used to compare mean species richness between the sites. Unconstrained nonmetric multidimensional scaling (nMDS) was carried out on fish grouped by family to visualize differences in fish assemblages between sites in two dimensions. nMDS was also carried out on the densities of commercial species present at the study sites. Permutational analysis of variance (PERMANOVA) was used to test for differences in fish families and commercial species between sites (Anderson 2001). A constrained ordination approach, canonical analysis of principal coordinates (CAP; Anderson and Willis 2003), and a similarity percentage (SIMPER) analysis were then used to identify the species that contributed most to differences in assemblages of commercial fish species between study sites (Clarke 1993).

3 Results

3.1 Habitat

We sampled 27 cells in the study area: 13 on Footprint Shallow, six on Footprint Flank, and eight on Piggy Bank, surveying a total of 66,470 m^2 of the seafloor (Table 1, Figure 1). Surveys in three of the cells had shorter track distances dues to technical issues. Depth range varied over the course of a cell from 10–83 m. Habitats encountered ranged from high-relief rock ridge to mud and sand seafloor. The AUV conducted dives at depths from 96–483 m.

A variety of habitat types were encountered at the study sites (Figure 2). Approximately 60% of the AUV images from Footprint Shallow were characterized primarily as mud and sand. Hard substrates observed here included cobble (18%), boulder (7%), and the greatest proportion of high-relief rock ridge (16%) seen among the three study sites. Footprint Flank was dominated by mud (98%), with very low proportions of gravel and boulder (~1%). Piggy Bank was characterized by mud (40%), cobble (19%), rock ridge (13%), and a higher proportion of boulder (26%) than the other two sites.

3.2 Fish

A total of 22,249 fishes in 54 taxa were observed during the study (Tables 2 and 3). We were able to identify 20 species of rockfish. Rockfish (genus *Sebastes*) and thornyheads (genus *Sebastolobus*) comprised 75% of the total number of fishes observed. The forward-looking camera was useful for some cases that were difficult to identify from the downward images. The most abundant rockfish species identified were halfbanded rockfish (*Sebastes semicinctus*), shortbelly rockfish (*S. jordani*), and squarespot rockfish (*S. hopkinsi*). Several commercially important species were recorded, including 12 observations of cowcod (*S. levis*), 24 of bocaccio (*S. paucispinis*), and one bronzespotted rockfish (*S. gilli*). There were 56 observations of lingcod, 34 Pacific hake, and 10 sablefish.

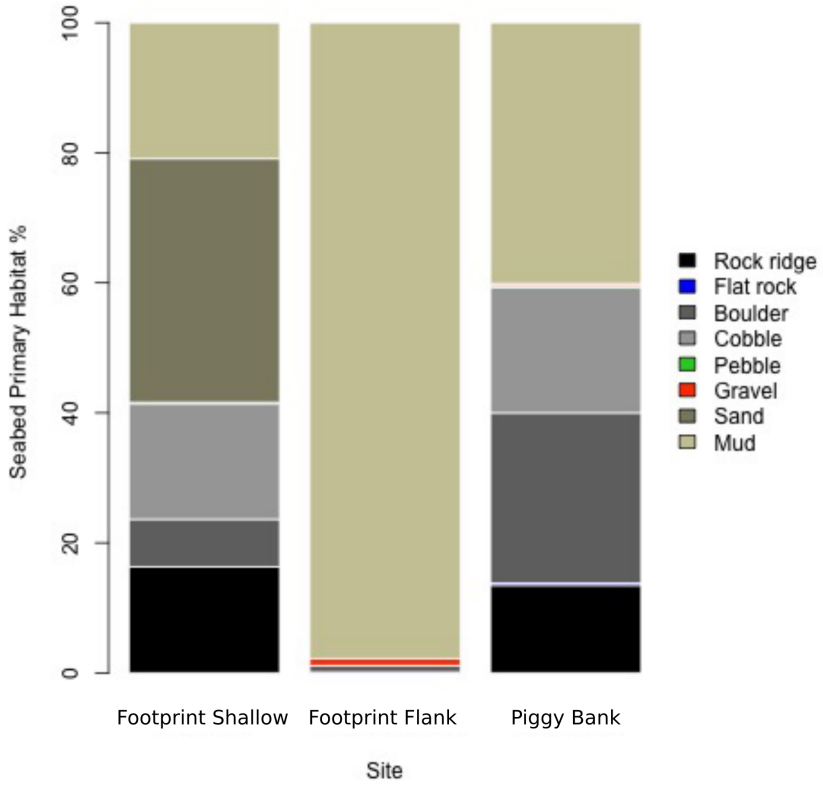

Figure 2. Percentage of the total primary habitat types (>50% of the habitat observed in frame) quantified from still photos taken by the AUV from The Footprint and Piggy Bank.

Table 2. Summary of observations (total observations and percent of total) for all species and taxonomic groups observed during the analysis of the AUV still images.

Common name	Scientific name	Total observations	% of total
Unidentified poachers	Agonidae	2,602	11.69
Sablefish	*Anoplopoma fimbria*	10	0.04
Sandpaper skate	*Bathyraja interrupta*	6	0.03
Unidentified sanddab	*Citharichthys* spp.	67	0.30
Unidentified sculpin	Cottidae	56	0.25
Deepsea sole	*Embassichthys bathybius*	3	0.01
Petrale sole	*Eopsetta jordani*	8	0.04
Unidentified hagfish	*Eptatretus* spp.	35	0.16
Rex sole	*Glyptocephalus zachirus*	98	0.44
Spotted ratfish	*Hydrolagus colliei*	37	0.17
Blacktail snailfish	Liparidae	3	0.01
Bigfin eelpout	*Lycodes cortezianus*	14	0.06
Slender sole	*Lyopsetta exilis*	167	0.75
Pacific hake	*Merluccius productus*	34	0.15
Dover sole	*Microstomus pacificus*	339	1.52
Lingcod	*Ophiodon elongatus*	56	0.25
Unidentified fishes	Osteichthyes	229	1.03
English sole	*Parophrys vetulus*	10	0.04
Bluebarred prickleback	*Plectobranchus evides*	4	0.02
Curlfin sole or hornyhead turbot	*Pleuronichthys decurrens* or *P. verticalis*	5	0.02
Unidentified flatfish	Pleuronectiformes	194	0.87
Longnose skate	*Raja rhina*	10	0.04
Unidentified skate	*Raja* spp.	1	0.00
Starry skate	*Raja stellulata*	7	0.03
Blackeye goby	*Rhinogobiops nicholsii*	2	0.01
Cat shark	Scyliorhinidae	1	0.00
Aurora rockfish	*Sebastes aurora*	1	0.00
Greenspotted rockfish	*Sebastes chlorostictus*	24	0.11
Starry rockfish	*Sebastes constellatus*	21	0.09
Splitnose rockfish	*Sebastes diploproa*	15	0.07
Greenstriped rockfish	*Sebastes elongatus*	46	0.21
Bronzespotted rockfish	*Sebastes gilli*	1	0.00
Chilipepper	*Sebastes goodei*	2	0.01
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	78	0.35
Squarespot rockfish	*Sebastes hopkinsi*	657	2.95
Shortbelly rockfish	*Sebastes jordani*	1,740	7.82
Cowcod	*Sebastes levis*	12	0.05
Blackgill rockfish	*Sebastes melanostomus*	25	0.11
Vermilion rockfish	*Sebastes miniatus*	9	0.04
Bocaccio	*Sebastes paucispinis*	24	0.11
Greenblotched rockfish	*Sebastes rosenblatti*	2	0.01
Flag rockfish	*Sebastes rubrivinctus*	24	0.11
Bank rockfish	*Sebastes rufus*	378	1.70
Stripetail rockfish	*Sebastes saxicola*	63	0.28

Table 2 (continued). Summary of observations for all species and taxonomic groups.

Common name	Scientific name	Total observations	% of total
Halfbanded rockfish	*Sebastes semicinctus*	1,812	8.14
Unidentified rockfishes	*Sebastes* spp.	3,497	15.72
Pygmy rockfish	*Sebastes wilsoni*	50	0.22
Sharpchin rockfish	*Sebastes zacentrus*	3	0.01
Shortspine thornyhead	*Sebastolobus alascanus*	35	0.16
Unidentified thornyheads	*Sebastolobus* spp.	431	1.94
Unidentified pricklebacks	Unidentified pricklebacks	56	0.25
Unidentified *Sebastomus*	Unidentified *Sebastomus*	7,765	34.90
Unidentified combfish	*Zaniolepis* spp.	1,069	4.80
Unidentified eelpout	Zoarcidae	411	1.85

Table 3. Number of selected species of interest from the AUV dives at depths of 99–486 m on The Footprint and Piggy Bank, October 2011. Taxa in gray text were found only on Footprint Shallow and Footprint Flank.

Common name	Scientific name	Total observations	% of total
Sablefish	*Anoplopoma fimbria*	10	0.04
Deepsea sole	*Embassichthys bathybius*	3	0.01
Petrale sole	*Eopsetta jordani*	8	0.04
Rex sole	*Glytocephalus zachirus*	98	0.44
Slender sole	*Lyopsetta exilis*	167	0.75
Pacific hake	*Merluccius productus*	34	0.15
Dover sole	*Microstomus pacificus*	339	1.52
Lingcod	*Ophiodon elongatus*	56	0.25
English sole	*Parophrys vetulus*	10	0.04
Aurora rockfish	*Sebastes aurora*	1	0.00
Greenspotted rockfish	*Sebastes chlorostictus*	24	0.11
Starry rockfish	*Sebastes constellatus*	21	0.09
Splitnose rockfish	*Sebastes diploproa*	15	0.07
Greenstriped rockfish	*Sebastes elongatus*	46	0.21
Bronzespotted rockfish	*Sebastes gilli*	1	0.00
Chilipepper	*Sebastes goodei*	2	0.01
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	78	0.35
Squarespot rockfish	*Sebastes hopkinsi*	657	2.95
Shortbelly rockfish	*Sebastes jordani*	1,740	7.82
Cowcod	*Sebastes levis*	12	0.05
Blackgill rockfish	*Sebastes melanostomus*	25	0.11
Vermilion rockfish	*Sebastes miniatus*	9	0.04
Bocaccio	*Sebastes paucispinis*	24	0.11
Greenblotched rockfish	*Sebastes rosenblatti*	2	0.01
Flag rockfish	*Sebastes rubrivinctus*	24	0.11
Bank rockfish	*Sebastes rufus*	378	1.70
Stripetail rockfish	*Sebastes saxicola*	63	0.28

Table 3 (continued). Number of selected species of interest from the AUV dives.

Common name	Scientific name	Total observations	% of total
Halfbanded rockfish	*Sebastes semicinctus*	1,812	8.14
Unidentified rockfish	*Sebastes* spp.	3,497	15.72
Pygmy rockfish	*Sebastes wilsoni*	50	0.22
Sharpchin rockfish	*Sebastes zacentrus*	3	0.01
Shortspine thornyhead	*Sebastolobus alascanus*	35	0.16
Unidentified thornyheads	*Sebastolobus* spp.	431	1.94
Unidentified *Sebastomus*	*Sebastomus* spp.	7,765	34.90

Table 4. Abundance estimates of the total number of fish per site.

Site	Site area (m^2)	Estimate of total number of fish	Lower 90% CI	Upper 90% CI	CV
Footprint Shallow	4,051,623	2,494,112	1,888,195	3,153,596	0.15
Footprint Flank	11,642,729	2,652,504	1,870,894	3,353,870	0.17
Piggy Bank	5,110,815	365,306	298,308	442,072	0.12

The total number of fish estimated on Footprint Shallow was 2,494,112 (Table 4). The fish assemblage at this site was dominated by rockfish in terms of abundance. The three most abundant groups were unidentified *Sebastomus* spp. (1,146,716), unidentified rockfishes (418,978), and halfbanded rockfish (270,173; Table 5). Shortbelly (239,473), squarespot (99,517), and bank rockfish (19,812) were also abundant rockfish species at this site. Other species of commercial interest included cowcod (1,986), bocaccio (3,521), and lingcod (9,183).

At the deeper Footprint Flank, the estimated total number of fish was 2,652,504 (Table 4). Numerous unidentified rockfish and thornyheads were observed (Table 6). The most common rockfish identified were a species complex of chilipepper and shortbelly rockfish (36,171), stripetail rockfish(30,528), and bank rockfish (6,770). In contrast to Footprint Shallow, we observed sablefish (3,048) and Pacific hake (19,947), but no lingcod. The most abundant flatfishes were petrale (2,938), rex (72,897), and slender sole (106,787). Other species that were recorded on Footprint Flank but not on Footprint Shallow included sandpaper and longnose skate, bigfin eelpout, and two rockfish species—splitnose and blackgill.

The total number of fish estimated on Piggy Bank was 365,306 (Table 4). The most abundant taxa at this site were unidentified thornyheads (81,951), unidentified rockfishes (59,980), and unidentified poachers (51,637; Table 7). We observed sablefish (1,457) but no lingcod. The most common rockfish species were bank rockfish (50,048), shortspine thornyhead (6,754), and blackgill rockfish (6,012). Rockfish species common at The Footprint but not observed here included squarespot, shortbelly, and halfbanded rockfish. Pacific hake was also much less abundant at this bank than at The Footprint (289).

The densities of lingcod and various rockfish species at the two sites are shown in Figure 3.

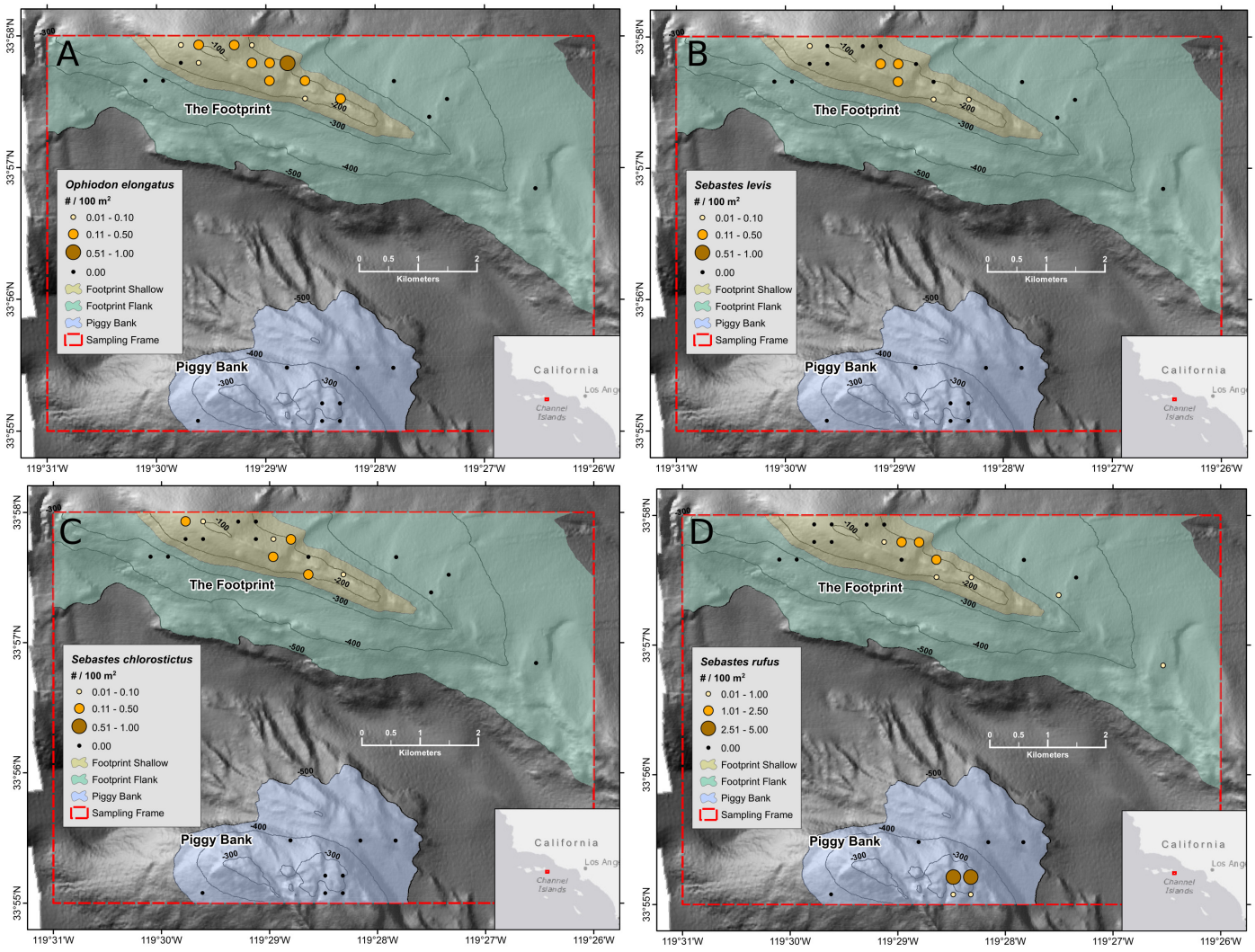

Figure 3. Densities (number per 100 m^2) of selected rockfish and lingcod observed at The Footprint and Piggy Bank during the AUV surveys: A) lingcod, B) cowcod, C) greenspotted rockfish, and D) bank rockfish.

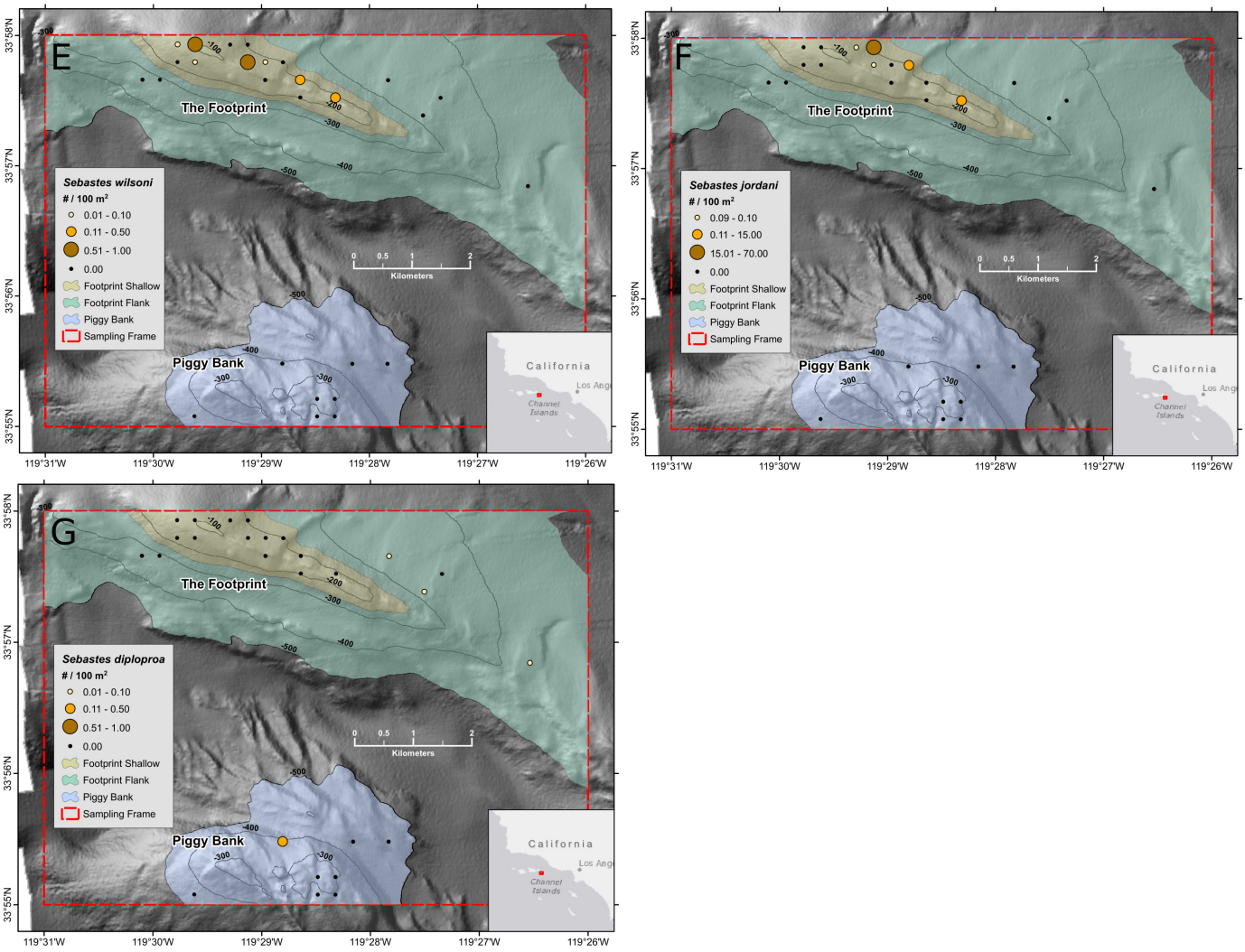

Figure 3 (continued). Densities (number per 100 m^2) of selected rockfish and lingcod observed at The Footprint and Piggy Bank during the AUV surveys: E) pygmy rockfish, F) shortbelly rockfish, and G) splitnose rockfish.

Table 5. Abundance estimates for Footprint Shallow.

Common name	Scientific name	Est. total # of fish	Lower 90% CI	Upper 90% CI	CV
Unidentified poachers	Agonidae	34,973	15,338	56,929	0.36
Unidentified sanddab	*Citharichthys* spp.	10,208	4,709	15,939	0.33
Unidentified sculpin	Cottidae	2,235	1,386	3,016	0.22
Petrale sole	*Eopsetta jordani*	436	146	877	0.52
Rex sole	*Glyptocephalus zachirus*	157	0	444	0.89
Spotted ratfish	*Hydrolagus colliei*	3,077	1,202	5,195	0.40
Slender sole	*Lyopsetta exilis*	861	0	2,662	0.98
Dover sole	*Microstomus pacificus*	7,908	4,029	12,686	0.34
Lingcod	*Ophiodon elongatus*	9,183	5,742	13,069	0.24
Unidentified fishes	Osteichthyes	8,465	5,409	11,989	0.23
English sole	*Parophrys vetulus*	724	146	1,471	0.54
Bluebarred prickleback	*Plectobranchus evides*	596	0	1,492	0.74
Curlfin sole or hornyhead turbot	*Pleuronichthys decurrens* or *P. verticalis*	828	0	1,862	0.67
Unidentified flatfish	Pleuronectiformes	6,452	2,970	10,515	0.36
Unidentified skate	*Raja* spp.	149	0	448	0.96
Starry skate	Raja stellulata	1,071	300	2,099	0.53
Blackeye goby	*Rhinogobiops nicholsii*	303	0	919	0.97
Greenspotted rockfish	*Sebastes chlorostictus*	4,047	1,795	6,701	0.37
Starry rockfish	*Sebastes constellatus*	3,828	726	7,586	0.54
Greenstriped rockfish	*Sebastes elongatus*	6,977	2,820	11,976	0.40
Bronzespotted rockfish	*Sebastes gilli*	162	0	460	0.92
Chilipepper	*Sebastes goodei*	283	0	581	0.66
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	886	0	2,240	0.80
Squarespot rockfish	*Sebastes hopkinsi*	99,517	12,667	226,959	0.68
Shortbelly rockfish	*Sebastes jordani*	239,473	1,118	683,658	0.86
Cowcod	*Sebastes levis*	1,986	901	3,237	0.37
Vermilion rockfish	*Sebastes miniatus*	1,344	299	2,587	0.53
Bocaccio	*Sebastes paucispinis*	3,521	1,041	6,423	0.46
Greenblotched rockfish	*Sebastes rosenblatti*	298	0	607	0.66
Flag rockfish	*Sebastes rubrivinctus*	3,789	1,727	6,176	0.35
Bank rockfish	*Sebastes rufus*	19,812	6,134	35,029	0.45
Stripetail rockfish	*Sebastes saxicola*	3,300	146	7,107	0.64
Halfbanded rockfish	*Sebastes semicinctus*	270,173	67,287	524,798	0.52
Unidentified rockfishes	*Sebastes* spp.	418,978	254,981	633,059	0.28
Pygmy rockfish	*Sebastes wilsoni*	7,605	2,150	13,981	0.46
Sharpchin rockfish	*Sebastes zacentrus*	306	0	895	0.94
Unidentified pricklebacks	Unidentified pricklebacks	4,056	682	8,425	0.60
Unidentified *Sebastomus*	Unidentified *Sebastomus*	1,146,716	763,024	1,547,627	0.21
Unidentified combfishes	*Zaniolepis* spp.	155,265	114,959	203,129	0.18
Unidentified eelpout	Zoarcidae	897	150	1,779	0.55

Table 6. Abundance estimates for Footprint Flank.

Common name	Scientific name	Est. total # of fish	Lower 90% CI	Upper 90% CI	CV
Unidentified poachers	Agonidae	1,365,460	847,577	1,823,268	0.22
Sablefish	*Anoplopoma fimbria*	3,048	529	5,646	0.49
Sandpaper skate	*Bathyraja interrupta*	3,285	1,576	5,029	0.31
Unidentified sculpin	Cottidae	29,599	12,839	50,299	0.38
Petrale sole	*Eopsetta jordani*	2,938	0	6,352	0.65
Rex sole	*Glyptocephalus zachirus*	72,897	30,273	117,378	0.36
Spotted ratfish	*Hydrolagus colliei*	3,813	529	6,902	0.48
Blacktail snailfish	Liparidae	2,268	0	5,375	0.72
Bigfin eelpout	*Lycodes cortezianus*	11,602	0	34,876	0.95
Slender sole	*Lyopsetta exilis*	106,787	71,220	141,939	0.20
Pacific hake	*Merluccius productus*	19,947	7,326	33,266	0.40
Dover sole	*Microstomus pacificus*	115,134	76,929	152,465	0.20
Unidentified fishes	Osteichthyes	85,608	49,537	120,357	0.26
English sole	*Parophrys vetulus*	3,007	896	5,441	0.48
Unidentified flatfish	Pleuronectiformes	85,025	50,208	111,671	0.21
Longnose skate	*Raja rhina*	1,735	0	3,453	0.56
Splitnose rockfish	*Sebastes diploproa*	3,202	830	5,753	0.49
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	36,171	1,018	81,658	0.64
Blackgill rockfish	*Sebastes melanostomus*	905	0	2,692	0.93
Bank rockfish	*Sebastes rufus*	6,770	0	15,270	0.67
Stripetail rockfish	*Sebastes saxicola*	30,528	2,318	66,075	0.63
Halfbanded rockfish	*Sebastes semicinctus*	1,042	0	3,054	0.90
Unidentified rockfishes	*Sebastes* spp.	355,368	176,288	620,495	0.38
Shortspine thornyhead	*Sebastolobus alascanus*	2,600	0	5,116	0.58
Unidentified thornyheads	*Sebastolobus* spp.	24,863	509	56,640	0.75
Unidentified *Sebastomus*	Unidentified *Sebastomus*	14,302	1,588	36,017	0.74
Unidentified combfishes	*Zaniolepis* spp.	31,739	0	64,247	0.59
Unidentified eelpout	Zoarcidae	225,165	60,543	491,252	0.58

Table 7. Abundance estimates for Piggy Bank.

Common name	Scientific name	Est. total # of fish	Lower 90% CI	Upper 90% CI	CV
Unidentified poachers	Agonidae	51,637	35,597	71,132	0.21
Sablefish	*Anoplopoma fimbria*	1,457	514	2,518	0.43
Sandpaper skate	*Bathyraja interrupta*	172	0	512	0.91
Unidentified sculpin	Cottidae	876	275	1,559	0.48
Deepsea sole	*Embassichthys bathybius*	765	282	1,331	0.45
Unidentified hagfish	*Eptatretus* spp.	7,211	2,015	13,302	0.47
Rex sole	*Glyptocephalus zachirus*	1,922	849	2,935	0.32
Spotted ratfish	*Hydrolagus colliei*	2,299	576	4,152	0.49
Slender sole	*Lyopsetta exilis*	173	0	498	0.93
Pacific hake	*Merluccius productus*	289	0	870	0.95
Dover sole	*Microstomus pacificus*	29,141	22,402	36,267	0.14
Unidentified fishes	Osteichthyes	4,716	1,957	7,834	0.37
Unidentified flatfish	Pleuronectiformes	2,442	549	4,808	0.55
Longnose skate	*Raja rhina*	1,306	0	4,094	0.95
Cat shark	Scyliorhinidae	166	0	512	0.96
Aurora rockfish	*Sebastes aurora*	163	0	350	0.94
Splitnose rockfish	*Sebastes diploproa*	3068	0	9509	0.97
Blackgill rockfish	*Sebastes melanostomus*	6012	341	14148	0.71
Bocaccio	*Sebastes paucispinis*	302	0	893	0.93
Bank rockfish	*Sebastes rufus*	50048	4219	98997	0.57
Unidentified rockfishes	*Sebastes* spp.	59980	34997	87344	0.26
Sharpchin rockfish	*Sebastes zacentrus*	173	0	498	0.92
Shortspine thornyhead	*Sebastolobus alascanus*	6,754	3,108	10,998	0.35
Unidentified thornyheads	*Sebastolobus* spp.	81,951	44,784	120,693	0.29
Unidentified pricklebacks	Unidentified pricklebacks	7,496	1,656	15,988	0.58
Unidentified *Sebastomus*	Unidentified *Sebastomus*	44,947	19,373	71,042	0.36
Unidentified combfish	*Zaniolepis* spp.	294	0	893	0.93
Unidentified eelpout	Zoarcidae	602	0	1,215	0.61

Fish assemblages varied between the shallow and deep sites at The Footprint and between the two banks. The total number of species observed was highest at Footprint Shallow (SR = 27), followed by Footprint Flank (SR = 17) and Piggy Bank (SR = 16); however, the areas surveyed by the AUV at the three sites were different. The sample-based rarefaction curves in Figure 4 show that, for an equivalent number of samples, the pattern was the same: mean species richness was highest at Footprint Shallow, then Footprint Flank, and lowest at Piggy Bank. The clustering of points on the unconstrained nMDS ordination of fish family densities highlighted differences between the sites (Figure 5). Footprint Shallow was characterized by rockfish, lingcod and combfish, Gobiidae (mainly blackeye goby), sanddabs, and pricklebacks. The deeper Footprint Flank site was characterized by abundant flatfishes, softnosed skates, Pacific hake, snailfish, sculpins, and large numbers of poachers. Piggy Bank was characterized by the presence of sablefish, eelpouts, hagfish (which were only observed at Piggy Bank), and a single observation of a catshark.
The differences in fish families present at the study sites were statistically significant (PERMANOVA, pseudo-$F = 15.83$, $P < 0.001$). The constrained CAP ordination (maximizes differences between sites) showed that Footprint Shallow was characterized by rockfish and lingcod, and Footprint Flank by flatfish and poachers (Appendix B).

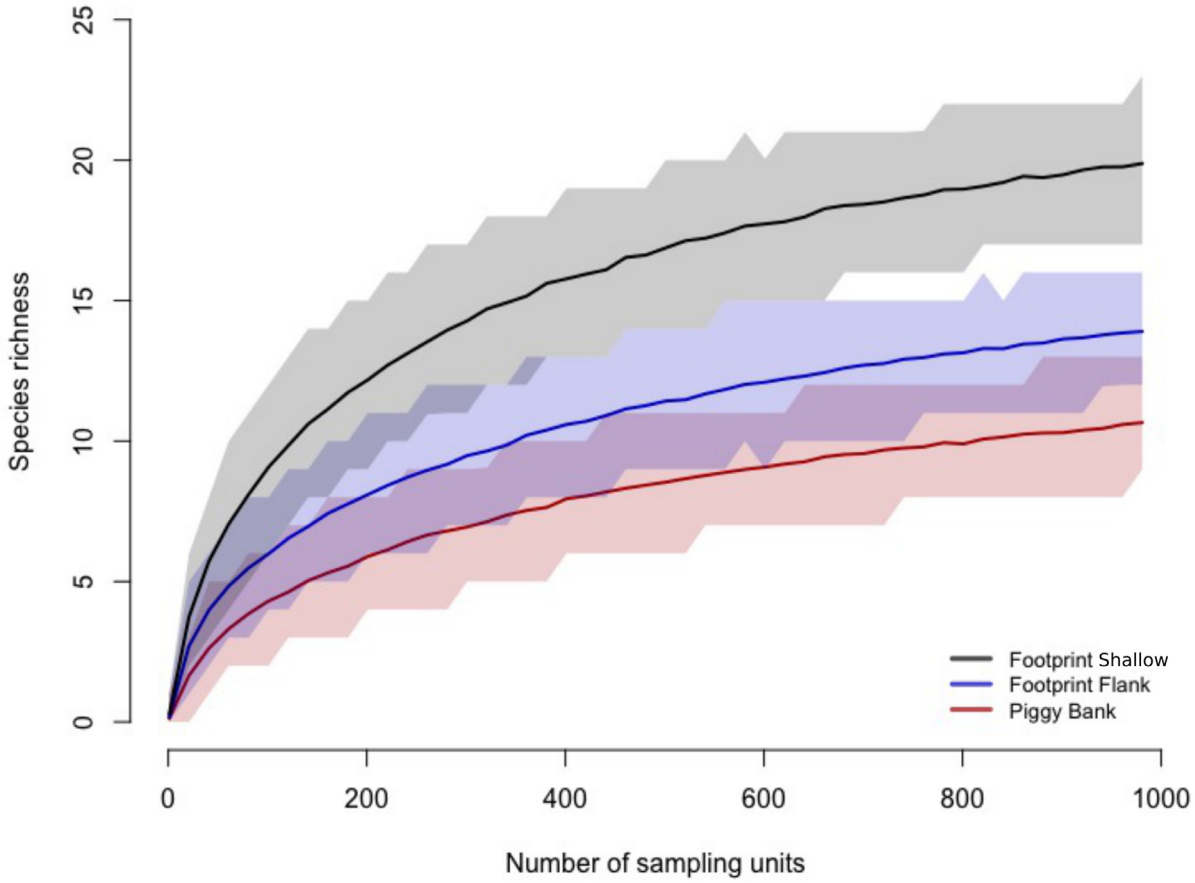

Figure 4. Sample-based species rarefaction curves for the three sites. Curves represent changes in species richness at each site with sampling intensity. Curves were constructed by plotting mean species richness of 1,000 bootstrap AUV image samples for each sample size. Shaded areas represent the 90% CI of the species richness for each sample size.

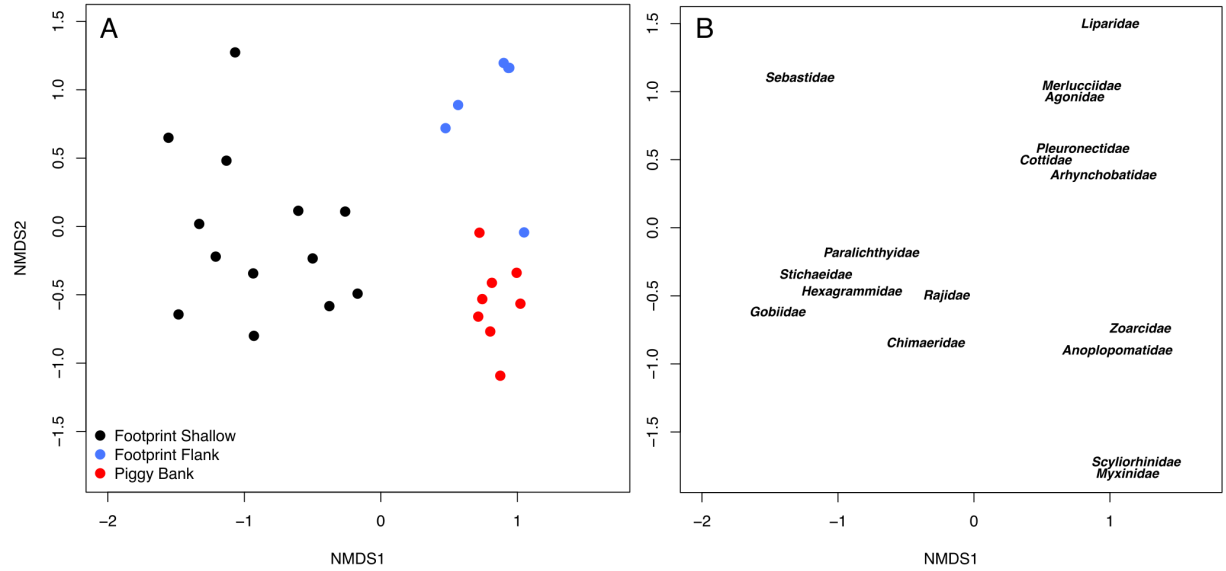

Figure 5. A) nMDS ordination showing similarities in fish families present at the study sites. The distance between points relates to similarities in assemblage composition; points close together represent cells with more-similar fish assemblages than those farther apart. B) The position of the taxon names on the ordination is the weighted average of the site scores, where the weights are the densities of each family in the original data.

When a subset of commercially important species (see Table 3 for species list) was analyzed, the nMDS ordination highlighted additional differences between the sites (Figure 6). Although most rockfish species were generally associated with Footprint Shallow, aurora rockfish was only observed at Piggy Bank, and splitnose and blackgill rockfish were only recorded at Footprint Flank and Piggy Bank. These differences in assemblages among sites were statistically significant (PERMANOVA, pseudo-$F = 5.31$, $P < 0.001$). The results of the SIMPER analysis indicate that the species that contributed most to differences between the shallow and deep Footprint sites were halfbanded rockfish, shortbelly rockfish, and squarespot rockfish (characteristic of Footprint Shallow) and the flatfishes slender sole and Dover sole (associated with Footprint Flank). Differences between Footprint Shallow and Piggy Bank were mainly driven by the high abundance of various rockfish species at the former. The species driving the differences between Footprint Flank and Piggy Bank were the flatfish at Footprint Flank and bank rockfish at Piggy Bank. The CAP analysis on commercial species showed that halfbanded, shortbelly, and squarespot rockfish were characteristic of The Footprint and bank rockfish of Piggy Bank (Appendix B).

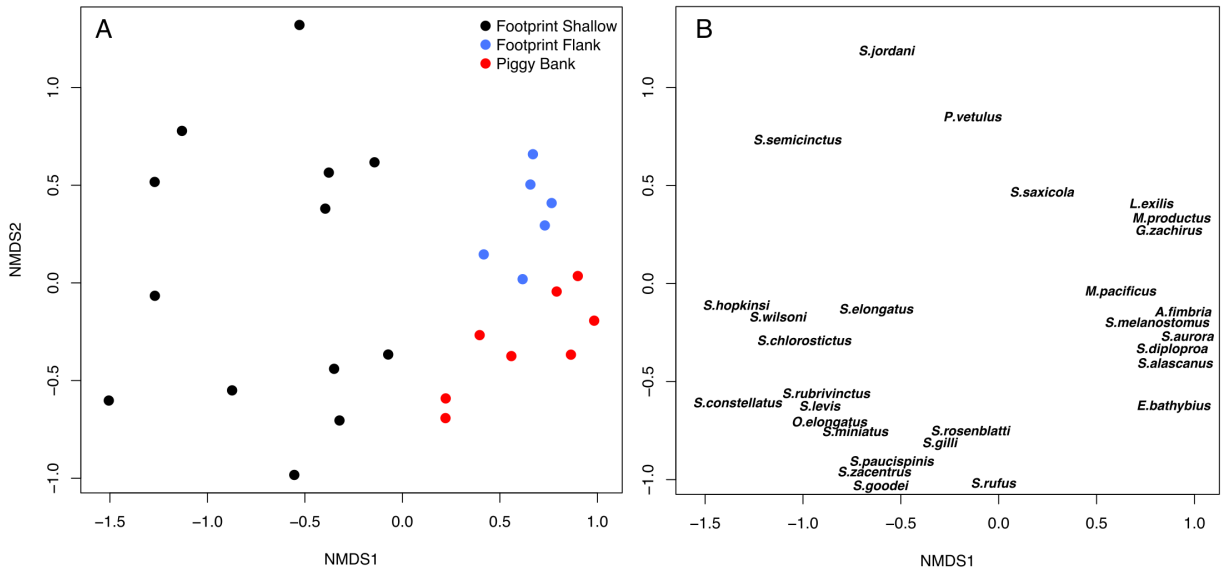

Figure 6. A) nMDS ordination showing similarities in fish species assemblages present at the study sites. The distance between points relates to similarities in assemblage composition; points close together represent cells with more-similar fish assemblages than those farther apart. B) The position of the taxon names on the ordination is the weighted average of the site scores, where the weights are the densities of species in the original data.

Bootstrapped estimates of total biomass for the three sites were 107,915 kg at Footprint Shallow, 83,205 kg at Footprint Flank, and 55,439 kg at Piggy Bank (Table 8). At Footprint Shallow, unidentified *Sebastomus* spp. (47,264 kg), unidentified rockfish (14,270 kg), and bank rockfish (8,153 kg) made up 62% of the biomass (Table 9). Other rockfish species that also contributed significantly to biomass (>3%) at this site were halfbanded rockfish, shortbelly rockfish, and bocaccio. Lingcod contributed nearly 7% of the biomass at this site.

Deeper at Footprint Flank, unidentified rockfish (19,698 kg), Dover sole (13,889 kg), and rex sole (13,361 kg) made up 57% of the biomass (Table 10). Sablefish made up 6.5% of the biomass (4,828 kg), and Pacific hake 2.5% (2,037 kg). The rockfish that contributed most to biomass at Footprint Flank (after unidentified rockfish) were bank rockfish, a species complex of chillipepper and shortbelly rockfish, and stripetail rockfish.

At Piggy Bank, the groups that contributed most to biomass (61%) were bank rockfish (19,856 kg), unidentified rockfish (7,441 kg), and Dover sole (7,299 kg; Table 11). Other fish groups with the greatest biomass (apart from unidentified *Sebastomus* and unidentified thornyheads) were shortspine thornyhead (2,224 kg), blackgill rockfish (646 kg), and bocaccio (562 kg). Sablefish and Pacific hake contributed 2.3% and 0.2% of the biomass, respectively, at Piggy Bank.

The mean lengths of all the species measured in the AUV survey are reported in Table 12, alongside the means derived from the trawl survey data. Histograms of the lengths of the most abundant species ($n > 50$) observed in the AUV imagery are presented in Figure 7. Side-by-side histograms for six species that were abundant in both the AUV and trawl datasets are shown in Figure 8. There were significant differences in the mean lengths derived from the AUV stereo imagery and trawl survey measurements for these species: Dover sole ($H = 17.02$, df = 1, $P < 0.001$), lingcod ($H = 62.04$, df = 1, $P < 0.001$), squarespot rockfish ($H = 35.36$, df = 1, $P < 0.001$), shortbelly rockfish ($H = 165.44$, df = 1, $P < 0.001$), stripetail rockfish ($H = 39.05$, df = 1, $P < 0.001$), and halfbanded rockfish($H = 20.64$, df = 1, $P < 0.001$). The mean lengths of lingcod and stripetail rockfish measured in AUV imagery were longer than those in the trawl survey, whereas the mean lengths of Dover sole and squarespot, shortbelly, and halfbanded rockfish were longer in the trawl survey data.

Table 8. Total biomass estimates for each site.

Site	Site area (m^2)	Est. fish biomass (kg)	Lower 90% CI	Upper 90% CI	SD	CV
Footprint Shallow	4,051,623	107,915	73,283	144,007	5.24	0.20
Footprint Flank	11,642,729	83,205	63,824	105,619	1.10	0.15
Piggy Bank	5,110,815	55,439	37,319	75,205	2.21	2.21

Table 9. Biomass estimates (in kg) per species/group for Footprint Shallow.

Common name	Scientific name	Est. fish biomass	Lower 90% CI	Upper 90% CI	CV
Unidentified sanddab	*Citharichthys* spp.	1,655	829	2,587	0.34
Petrale sole	*Eopsetta jordani*	583	83	1,175	0.55
Rex sole	*Glyptocephalus zachirus*	5	0	17	0.96
Spotted ratfish	*Hydrolagus colliei*	23	10	39	0.39
Slender sole	*Lyopsetta exilis*	42	0	122	0.93
Dover sole	*Microstomus pacificus*	724	355	1,117	0.32
Lingcod	*Ophiodon elongatus*	7,083	3,775	10,722	0.30
English sole	*Parophrys vetulus*	292	37	586	0.56
Curlfin sole or hornyhead turbot	*Pleuronichthys decurrens* or *P. verticalis*	45	0	121	0.80
Unidentified flatfish	Pleuronectiformes	585	321	894	0.30
Unidentified skate	*Raja* spp.	102	0	326	0.97
Starry skate	*Raja stellulata*	1,218	217	2,345	0.51
Greenspotted rockfish	*Sebastes chlorostictus*	1,568	594	2,939	0.46
Starry rockfish	*Sebastes constellatus*	436	140	752	0.48
Greenstriped rockfish	*Sebastes elongatus*	876	255	1,730	0.52
Bronzespotted rockfish	*Sebastes gilli*	258	0	757	0.94
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	214	28	531	0.72
Squarespot rockfish	*Sebastes hopkinsi*	4,887	638	11,688	0.69
Shortbelly rockfish	*Sebastes jordani*	5,497	69	13,120	0.74
Cowcod	*Sebastes levis*	2,225	623	4,035	0.46
Vermilion rockfish	*Sebastes miniatus*	2,211	371	4,287	0.52
Bocaccio	*Sebastes paucispinis*	2,902	849	5,156	0.45
Greenblotched rockfish	*Sebastes rosenblatti*	306	0	633	0.64
Flag rockfish	*Sebastes rubrivinctus*	1,339	353	2,575	0.50
Bank rockfish	*Sebastes rufus*	8,153	2,365	15,305	0.49
Stripetail rockfish	*Sebastes saxicola*	185	2	374	0.64
Halfbanded rockfish	*Sebastes semicinctus*	6,860	1,288	13,208	0.51
Unidentified rockfishes	*Sebastes* spp.	14,270	8,699	20,327	0.24
Pygmy rockfish	*Sebastes wilsoni*	216	66	384	0.45
Sharpchin rockfish	*Sebastes zacentrus*	206	0	599	0.94
Unidentified *Sebastomus*	Unidentified *Sebastomus*	47,264	28,474	66,734	0.25

Table 10. Biomass estimates (in kg) per species/group for Footprint Flank.

Common name	Scientific name	Est. fish biomass	Lower 90% CI	Upper 90% CI	CV
Sablefish	*Anoplopoma fimbria*	4,828	334	12,470	0.77
Sandpaper skate	*Bathyraja interrupta*	1,960	504	3,610	0.49
Petrale sole	*Eopsetta jordani*	1,576	0	3,920	0.76
Rex sole	*Glyptocephalus zachirus*	13,361	6,238	20,505	0.32
Spotted ratfish	*Hydrolagus colliei*	14	0	28	0.58
Slender sole	*Lyopsetta exilis*	7,975	5,732	9,808	0.16
Pacific hake	*Merluccius productus*	2,037	797	3,465	0.41
Dover sole	*Microstomus pacificus*	13,889	8,955	19,480	0.23
English sole	*Parophrys vetulus*	830	279	1,383	0.44
Unidentified flatfish	Pleuronectiformes	5,969	3,597	8,341	0.24
Longnose skate	*Raja rhina*	310	0	906	0.88
Splitnose rockfish	*Sebastes diploproa*	164	53	281	0.43
Chilipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	1,828	181	4,351	0.70
Blackgill rockfish	*Sebastes melanostomus*	93	0	272	0.90
Bank rockfish	*Sebastes rufus*	2,559	0	6,343	0.72
Stripetail rockfish	*Sebastes saxicola*	1,702	128	3,365	0.57
Halfbanded rockfish	*Sebastes semicinctus*	62	0	182	0.90
Unidentified rockfishes	*Sebastes* spp.	19,698	8,132	33,247	0.48
Shortspine thornyhead	*Sebastolobus alascanus*	312	0	852	0.83
Unidentified thornyheads	*Sebastolobus* spp.	1,354	21	3,770	0.85
Unidentified *Sebastomus*	Unidentified *Sebastomus*	2,050	187	5,343	0.76

Table 11. Biomass estimates (in kg) per species/group for Piggy Bank.

Common name	Scientific name	Est. fish biomass	Lower 90% CI	Upper 90% CI	CV
Sablefish	*Anoplopoma fimbria*	1,284	86	3,139	0.73
Sandpaper skate	*Bathyraja interrupta*	268	0	853	0.95
Deepsea sole	*Embassichthys bathybius*	393	100	754	0.55
Rex sole	*Glyptocephalus zachirus*	643	199	1,042	0.40
Spotted ratfish	*Hydrolagus colliei*	16	4	31	0.49
Slender sole	*Lyopsetta exilis*	19	0	56	0.96
Pacific hake	*Merluccius productus*	88	0	256	0.89
Dover sole	*Microstomus pacificus*	7,299	5,596	9,487	0.17
Unidentified flatfish	Pleuronectiformes	363	124	619	0.42
Longnose skate	*Raja rhina*	3,374	0	10,012	0.92
Aurora rockfish	*Sebastes aurora*	12	0	37	0.98
Splitnose rockfish	*Sebastes diploproa*	429	0	1,301	0.92
Blackgill rockfish	*Sebastes melanostomus*	646	0	1,575	0.74
Bocaccio	*Sebastes paucispinis*	562	0	1,708	0.91
Bank rockfish	*Sebastes rufus*	19,856	2,705	37,471	0.53
Unidentified rockfishes	*Sebastes* spp.	7,441	4,230	11,033	0.28
Sharpchin rockfish	*Sebastes zacentrus*	57	0	180	0.95
Shortspine thornyhead	*Sebastolobus alascanus*	2,224	857	3,737	0.39
Unidentified thornyheads	*Sebastolobus* spp.	4,076	2,643	5,382	0.21
Unidentified *Sebastomus*	Unidentified *Sebastomus*	6,889	3,045	10,614	0.33

Table 12. Comparison of mean species lengths as measured from the AUV stereo camera imagery and from the 2011 West Coast Groundfish Bottom Trawl Survey in the Southern California Bight (depth <500 m). The number of individuals measured is also shown.

		AUV		Trawl survey	
Common name	**Species**	**Mean length**	**SD**	**Mean length**	**SD**
Sablefish	*Anoplopoma fimbria*	45.61	10.89	39.88	7.14
Sandpaper skate	*Bathyraja interrupta*	49.79	12.73	n/a	n/a
Deepsea sole	*Embassichthys bathybius*	32.48	8.15	n/a	n/a
Petrale sole	*Eopsetta jordani*	36.70	7.28	30.46	6.09
Rex sole	*Glyptocephalus zachirus*	22.03	4.95	24.56	6.59
Spotted ratfish	*Hydrolagus colliei*	37.12	7.78	17.45	3.29
Slender sole	*Lyopsetta exilis*	18.31	2.87	n/a	n/a
Pacific hake	*Merluccius productus*	23.16	3.08	25.86	9.48
Dover sole	*Microstomus pacificus*	24.27	6.20	25.91	5.20
Lingcod	*Ophiodon elongatus*	39.24	9.96	26.42	11.58
English sole	*Parophrys vetulus*	28.39	6.78	24.01	3.62
Longnose skate	*Raja rhina*	57.52	20.21	44.02	19.52
Starry skate	*Raja stellulata*	47.88	14.70	41.17	16.49
Aurora rockfish	*Sebastes aurora*	n/a	n/a	19.12	6.44
Greenspotted rockfish	*Sebastes chlorostictus*	26.32	8.66	22.90	7.58
Starry rockfish	*Sebastes constellatus*	13.96	9.87	n/a	n/a
Splitnose rockfish	*Sebastes diploproa*	21.87	4.64	17.07	6.59
Greenstriped rockfish	*Sebastes elongatus*	20.11	5.20	18.35	4.33
Bronzespotted rockfish	*Sebastes gilli*	n/a	n/a	n/a	n/a
Squarespot rockfish	*Sebastes hopkinsi*	13.77	3.14	16.39	3.53
Shortbelly rockfish	*Sebastes jordani*	12.65	1.99	14.32	6.59
Cowcod	*Sebastes levis*	34.32	19.43	18.57	8.83
Blackgill rockfish	*Sebastes melanostomus*	26.98	6.60	33.89	10.51
Vermilion rockfish	*Sebastes miniatus*	42.18	8.98	n/a	n/a
Bocaccio	*Sebastes paucispinis*	39.27	12.08	26.02	6.11
Greenblotched rockfish	*Sebastes rosenblatti*	37.32	1.55	n/a	n/a
Flag rockfish	*Sebastes rubrivinctus*	25.14	7.55	19.67	2.52
Bank rockfish	*Sebastes rufus*	29.37	5.52	28.50	9.19
Stripetail rockfish	*Sebastes saxicola*	15.04	3.85	12.41	2.10
Halfbanded rockfish	*Sebastes semicinctus*	10.51	2.37	11.23	2.35
Pygmy rockfish	*Sebastes wilsoni*	12.29	1.71	14.00	1.73
Sharpchin rockfish	*Sebastes zacentrus*	30.37	3.11	17.77	9.31
Shortspine thornyhead	*Sebastolobus alascanus*	29.12	6.39	22.15	7.69

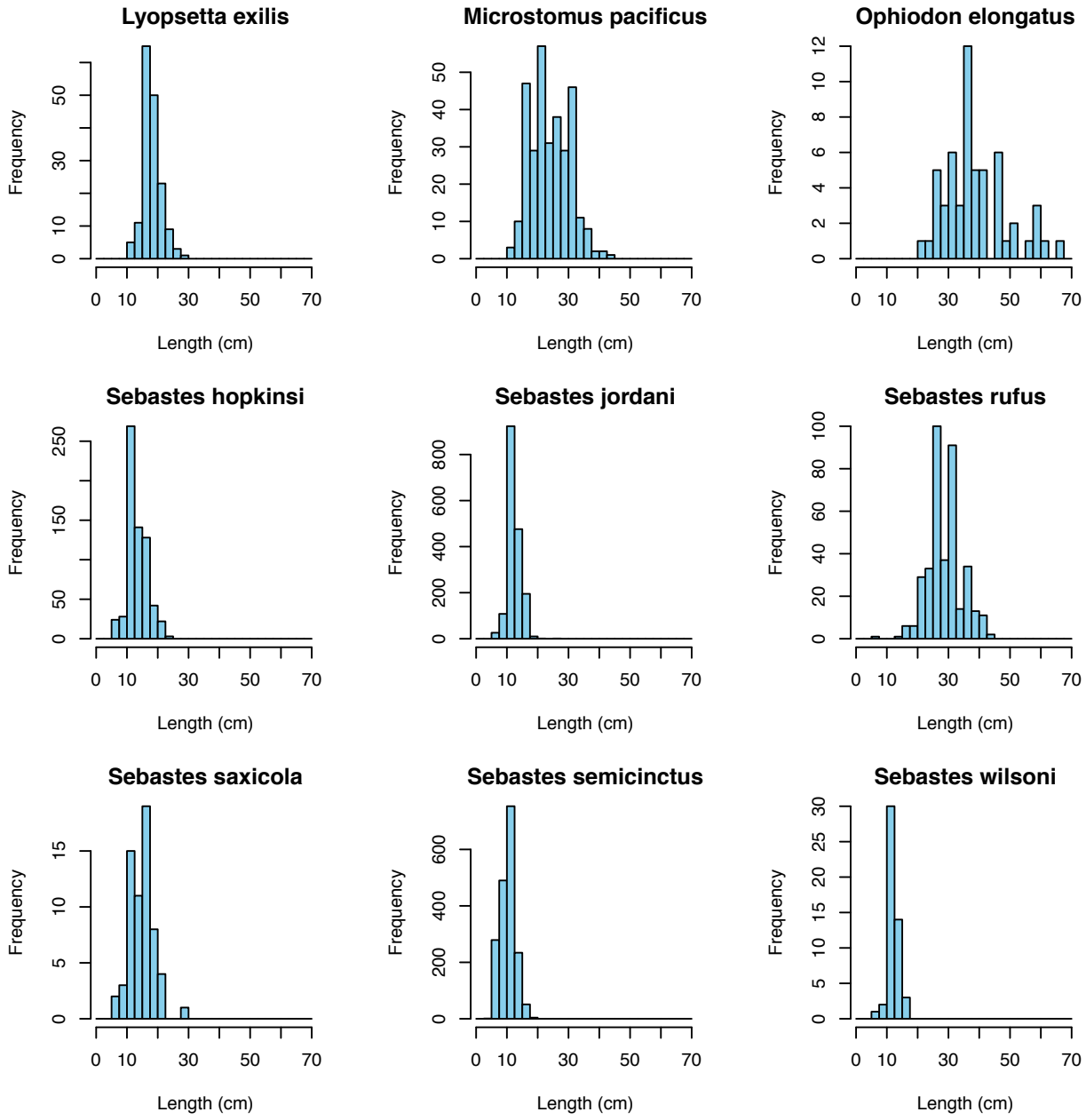

Figure 7. Size frequency distributions for the species observed by AUV (histograms were limited to species where more than 50 individuals were recorded).

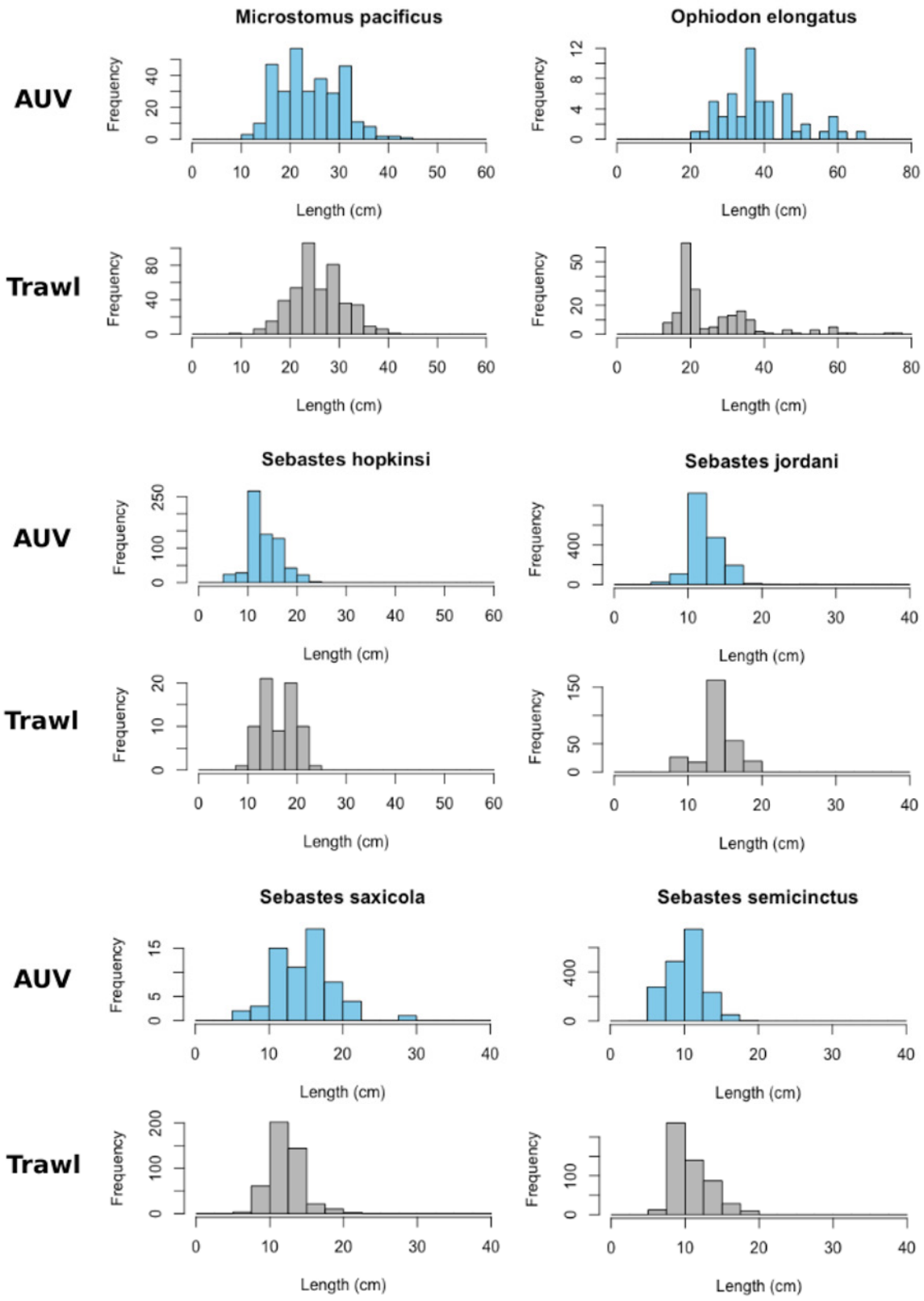

Figure 8. Comparisons of size histograms based on the AUV data (light blue) and 2011 West Coast Groundfish Bottom Trawl Survey (gray) in the Southern California Bight (depth <500 m). Histograms were limited to species with more than 50 individuals in both surveys.

4 Discussion

The AUV survey produced abundance estimates for 54 groundfish taxa and habitat data for two rocky banks off Southern California. It also provided information on the size distributions and biomass of commercially important species, including rockfishes and flatfishes. We observed significant differences in the fish assemblages present at our three study sites. Groundfish distributions are often influenced by substrate type and depth, which acts as a proxy for changes in many environmental variables such as temperature, light, and dissolved oxygen (Tolimieri et al. 2006). Many of the patterns that we observed may be related to differences in these factors.

The substrate at The Footprint ranged from a patchwork of high-relief rocky areas on the top part of the bank to low-relief mud deeper on the flanks. Footprint Shallow was characterized by the presence of commercially important species, including a diverse rockfish community and lingcod. The most abundant rockfish species at this site were halfbanded, shortbelly, and squarespot rockfish. These are dwarf species with relatively short life spans that often occur in schools (Love et al. 2002). Halfbanded and shortbelly rockfish occur in a large range of habitats from high-relief rock to sand and mud, whereas squarespot rockfish are found primarily near rocky outcrops and boulder fields (Love et al. 2002). The deeper site, Footprint Flank, had lower species diversity and a much higher proportion of flatfish, likely due to the large areas of mud, which is their typical habitat (Kramer et al. 1995). Pacific hake and sablefish, two species associated with deep, soft bottom substrates, were only observed at the deeper Footprint Flank site and not on Footprint Shallow. Similar species zonation patterns associated with changes in depth and substrate have been documented at numerous sites off the U.S. West Coast. Early studies at Heceta Bank in Oregon (1998–90) described a gradient from high-complexity rocky habitats characterized by the presence of rockfish and lingcod at shallow depths (<100 m) to deep mud slopes (>200 m) characterized by shortspine thornyhead and flatfishes (Tissot et al. 2008). Extensive submarine surveys in the Southern California Bight also identified distinct fish assemblages, including a midshelf assemblage (~100 m) associated with rocky, high-relief habitats, and a deep-shelf assemblage (~170 m) associated mainly with soft substrates or rock margins (Love et al. 2009). Small rockfish, including halfbanded, shortbelly, and squarespot rockfish, were also among the most-abundant species recorded by Love et al. (2007).

We observed differences in the fish species that were present at the two banks. Rockfish assemblages present at Piggy Bank were less diverse and were dominated by the presence of large numbers of thornyheads and bank rockfish. These differences are likely due to differences in depth rather than substrate, as Piggy Bank had hard and soft substrates in similar proportions to Footprint Shallow. Piggy Bank is deeper than The Footprint—the shallowest depth recorded by the AUV at Piggy Bank was 279 m, whereas the dives on the top of Footprint ranged from 99–226 m—and there were similarities between the fish present at Piggy Bank and the deeper Footprint Flank site. For example, Pacific hake and sablefish were both observed at these sites and not on Footprint Shallow. Other deeper-water species observed at these sites were snailfish (Footprint Flank) and catshark (Piggy Bank). The differences between the banks could also be due to Piggy Bank having slightly less high-relief rock ridge than The Footprint and more extensive areas of boulder. Juvenile and adult bank rockfish, the most common rockfish at Piggy Bank, are often found over high-relief boulder fields (Love et al. 2002). Thornyheads were commonly observed sitting on mud, which is characteristic of this species (Love et al. 2002).

4.1 Comparison of the AUV with the ROV and the SUB

We compared the AUV results with those of the ROV and the SUB (Stierhoff et al. 2013 and Yoklavich et al. 2013). All three survey methodologies showed similar characterization of the fish assemblages on Piggy Bank and The Footprint. However, differences in vehicles, sensors, survey protocols, and analysis methodologies made direct comparisons difficult. The different studies included different species groups. All fish observed were included in the AUV analysis, but the ROV and SUB analyses were based on a subset of commercially important species. The AUV was able to sample the deeper 400–500-m stratum on the flank of The Footprint, and to provide fish and habitat information that was not available from the ROV or SUB dives. As a result, abundance and biomass estimates for the banks are based on different survey areas. In addition, all tools reported densities by area, not volume, which also makes comparisons between estimates difficult. Volumetric density can be computed using stereo calibration parameters to estimate the joint camera-viewing volume and obtain absolute abundances of fishes (Williams et al. 2018). This enables standardized comparisons between different camera platforms and survey methodologies. A more-detailed stratification by habitat would also potentially provide more comparison across methods. Biomass estimates for the banks are also likely to be affected by the different fish length estimation methods. The ROV and the SUB used paired lasers as a scale against which to make length measurements, whereas the AUV used a paired stereo camera system. Studies have found that there can be significant differences in lengths obtained with these methods (Dunlop et al. 2015). Paired laser systems seem to be less accurate when targets are diagonal to the lasers. As differences in length are amplified when converted to biomass, this could have affected the estimates obtained with the different survey tools.

Despite these challenges, we are able to make some general comparisons between the results of the different surveys. The pattern of species diversity was similar among all three methodologies, with greater species richness at The Footprint and lower richness at Piggy Bank. The ROV and the SUB included records of rockfish species not identified by the AUV. More species were aggregated into taxonomic groups (i.e., unidentified rockfish, or *Sebastomus* spp.) in the AUV data. This could be due to the fact that the cameras on the AUV are positioned downward, which can lead to difficulties in identifying some rockfish species from the dorsal view. In addition, the AUV was programmed to fly at 4 m above the seafloor for some of the dives. This was to minimize the risk of getting caught in highly rugose terrain, but is too high for optimum identification of fish. Another contributing factor could be that video allows for fish to be viewed from multiple angles, which provides more opportunities to observe identifying features than still images. Differences could also be due to variation in the habitats that were surveyed by each method. For instance, the ROV and SUB carried out more surveys on the high-relief rocky Footprint Shallow than the AUV. Finally, differences between observers, and whether they are more inclined to "split" or "aggregate" species, could also contribute to this variation. Comparisons of fish counts of the same images by different observers suggest that this affects species richness estimates. The total number of fish estimated for both banks was 5,511,922 for the AUV (sum of the estimates from The Footprint and Piggy Bank), ~2,300,000 for the ROV (Stierhoff et al. 2013), and 2,368,819 for the SUB (Yoklavich et al. 2013). However, the AUV sampled a larger area and included both commercially important and noncommercial species.

4.2 Conclusions

Each of the three survey methods had strengths and weaknesses. The ROV and SUB are particularly well suited to surveying high-relief rocky habitat such as Footprint Shallow, where the areas under ledges can be observed. The ability to focus in on particular fish in real time improves the field of view and also improves identification of some fish species. An advantage of the AUV is that it does not need to be piloted like the ROV or SUB. This allows large amounts of data to be collected without human fatigue and can free up time for simultaneous operations or work to take place. The unmanned nature of the AUV also makes it safer to operate than a SUB, and its relatively small size can also be an advantage as it can be deployed off smaller vessels. In addition, the AUV's autonomous nature also means that line transects are more likely to be collected following a particular heading and at constant speed than by human-occupied vehicles or ROVs (visibly straighter tracklines), reducing potential bias. In this study, the use of paired stereo cameras on the AUV was an advantage because it allowed survey area and fish lengths to be estimated more easily and with improved accuracy and precision. The AUV is also particularly well adapted for surveying flatfishes and skates, due to the downward-facing cameras. However, during this survey it was clear that fish photographed at a distance of 4 m above the seafloor cannot be clearly identified. We have subsequently changed our protocol to survey at an altitude of 3 m above the seafloor or lower, and are developing guides to improve our ability to accurately identify fishes from the dorsal view.

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Appendix A

Table A-1. Fish length–weight relationships are described by the formula $W = a \times L^b$. This table includes the parameter estimates for *a* and *b* used in this study for each species or species complex.

Common name	Species	*a*	*b*	Sex	Reference[a]	Comment
Sablefish	*Anoplopoma fimbria*	0.001920	3.46400	both	Kodolov (1976)	
Sandpaper skate	*Bathyraja interrupta*	0.005020	3.03100	both	Orlov et al. (2006)	
Unidentified sanddab	*Citharichthys* spp.	0.009330	3.08000	both	FishBase Froese et al. (2014)	Bayesian length–weight est. borrowed from *C. sordidus*.
Deepsea sole	*Embassichthys bathybius*	0.008910	3.09000	both	FishBase Froese et al. (2014)	Bayesian length–weight est.
Petrale sole	*Eopsetta jordani*	0.004260	3.30600	both	Fadeev (2005)	
Rex sole	*Glytocephalus zachirus*	0.002840	3.53100	unsexed	Martin (1997)	
Spotted ratfish	*Hydrolagus colliei*	0.000250	2.75500	unsexed	Barnett et al. (2009)	
Slender sole	*Lyopsetta exilis*	0.008910	3.09000	both	FishBase Froese et al. (2014)	Bayesian length–weight est.
Pacific hake	*Merluccius productus*	0.034700	2.55600	males	Dark (1975)	
Dover sole	*Microstomus pacificus*	0.012220	2.93900	both	Fadeev (2005)	
Lingcod	*Ophiodon elongatus*	0.011300	2.99000	both	RecFIN	
English sole	*Parophrys vetulus*	0.014290	2.90400	both	Fadeev (2005)	
Curlfin sole or horneyhead turbot	*Pleuronichthys decurrens* or *P. verticalis*	0.008910	3.09000	both	FishBase Froese et al. (2014)	Bayesian length–weight est. borrowed from *P. decurrens*.
Unidentified flatfish	Pleuronectiformes	0.012220	2.93900	both	FishBase Froese et al. (2014)	Bayesian length–weight est. borrowed from *M. pacificus*.
Longnose skate	*Raja rhina*	0.002880	3.22000	both	FishBase Froese et al. (2014)	Bayesian length–weight est.
Unidentified skate	*Raja* spp.	0.002880	3.22000	both	FishBase Froese et al. (2014)	Bayesian length-weight est. borrowed from *R. rhina*.
Starry skate	*Raja stellulata*	0.002880	3.22000	both	FishBase Froese et al. (2014)	Bayesian length–weight est.
Aurora rockfish	*Sebastes aurora*	0.024400	2.83200	both	Wilkins et al. (1998)	
Greenspotted rockfish	*Sebastes chlorostictus*	0.009100	3.16320	both	Love et al. (1990)	
Starry rockfish	*Sebastes constellatus*	0.009700	3.15980	both	Love et al. (1990)	
Splitnose rockfish	*Sebastes diploproa*	0.004100	3.24400	both	PSMFC	
Greenstripe rockfish	*Sebastes elongatus*	0.007900	3.12750	both	Love et al. (1990)	

[a] FishBase can be found at https://www.fishbase.org/, RecFIN at https://www.recfin.org/, PSMFC at https://www.psmfc.org/.

Table A-1 (continued). Fish length–weight relationships are described by the formula $W = a \times L^b$. This table includes the parameter estimates for *a* and *b* used in this study for each species or species complex.

Common name	Species	*a*	*b*	Sex	Reference[a]	Comment
Bronzespotted rockfish	*Sebastes gilli*	0.017700	2.98070	both	PSMFC	
Chillipepper or shortbelly rockfish	*Sebastes goodei* or *S. jordani*	0.005613	3.16000	both	PSMFC	Borrowed from *S. jordani*.
Squarespot rockfish	*Sebastes hopkinsi*	0.014600	2.98400	both	Love et al. (1990)	
Shortbelly rockfish	*Sebastes jordani*	0.005600	3.16000	both	PSMFC	
Cowcod	*Sebastes levis*	0.010100	3.09330	both	Love et al. (1990)	
Blackgill rockfish	*Sebastes melanostomus*	0.012300	3.04200	both	Love et al. (1990)	
Vermilion rockfish	*Sebastes miniatus*	0.021570	2.92339	both	Love et al. (1990)	
Bocaccio	*Sebastes paucispinis*	0.016200	2.88100	female	Love et al. (1990)	
Greenblotched rockfish	*Sebastes rosenblatti*	0.011000	3.10570	both	Love et al. (1990)	
Flag rockfish	*Sebastes rubrivinctus*	0.020600	2.94310	both	RecFIN	
Bank rockfish	*Sebastes rufus*	0.007800	3.14690	both	Love et al. (1990)	
Stripetail rockfish	*Sebastes saxicola*	0.009300	3.12010	both	PSMFC	
Halfbanded rockfish	*Sebastes semicinctus*	0.012700	3.01600	female	Love et al. (1990)	
Unidentified rockfish	*Sebastes* spp.	0.014600	2.98400	both	Love et al. (1990)	Borrowed from *S. hopkinsi*.
Pygmy rockfish	*Sebastes wilsoni*	0.011900	3.02300	both	Moulton (1977)	Borrowed from *S. emphaeus*.
Sharpchin rockfish	*Sebastes zacentrus*	0.006000	3.28000	both	Wilkins et al. (1998)	
Shortspine thornyhead	*Sebastolobus alascanus*	0.003900	3.35700	both	Wakefield (1990)	
Unidentified thornyhead	*Sebastolobus* spp.	0.004900	3.26400	both	Taylor and Stevens (2014)	Borrowed from *S. alascanus*.
Unidentified *Sebastomus*	Unidentified *Sebastomus*	0.013200	2.97000	both	Love et al. (1990)	Borrowed from *S. ensifer*.

[a] PSMFC can be found at https://www.psmfc.org/, RecFIN at https://www.recfin.org/, PSMFC at https://www.psmfc.org/.

Appendix B

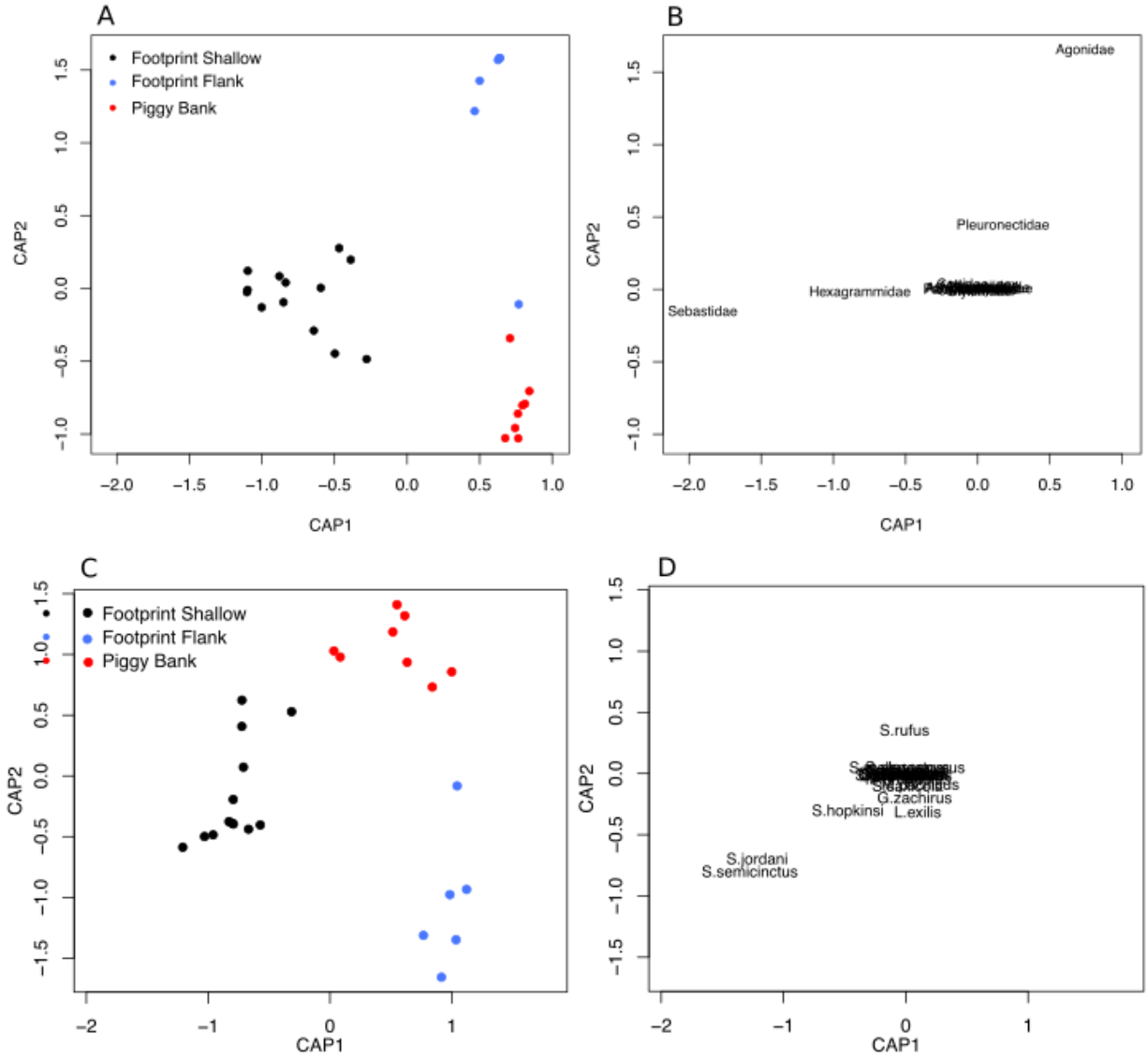

Figure B-1. Canonical Analysis of Principal coordinates (CAP). A) CAP ordination showing similarities in fish families present at the study sites. Points close together represent cells with more-similar fish assemblages than those farther apart. B) The position of the taxon names on the ordination is the weighted average of the site scores, where the weights are the densities of each family in the original data. C) CAP ordination showing similarities in fish species assemblages at the study sites. D) The position of the taxon names on the ordination is the weighted average of the site scores, where the weights are the densities of species in the original data.

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